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January 1996

RECONFIGURABLE ANTENNAS

University of Maryland

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RECONFIGURABLE ANTENNAS

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13. ABSTRACT (Maximum 200 words)
A radio frequency (RF) antenna was demonstrated by exciting charge carriers in a semiconductor. Using a common camera flash and a custom mask, portions of a four-inch diameter silicon wafer were illuminated to form a temporary electrically conductive pathway. The conductive path would momentarily mimic a thin-layer metallic antenna through which RF energy could be received or transmitted. Experiments in the 1-4 GHz range showed the optically-excited semiconductor antennas to be about 5 dB less efficient than similar dipole and bow-tie design metallic antennas. The silicon used had a carrier lifetime of approximately five microseconds when illuminated with an optical intensity of 10 watts per square centimeter. Changing illumination masks would allow the semiconductor antenna to be reconfigured to a variety of different antenna designs.

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Table of Contents

Summary

A simple reconfigurable antenna was demonstrated using a common camera flash and stock 4"-diameter silicon wafers in the 1-4 GHz range. The reconfigurable antenna was triangular, and about 5 dB less efficient than a metallic antenna of the same design. Optical intensity of only about 10 W/cm^2 was required for the silicon used whose mobility and carrier lifetime were about 10^3 $cm^2/V\text{-}s$ and 5 μs respectively.

Introduction

When a semiconductor is illuminated with light, the optical energy is absorbed, and free charge carriers are created which can conduct electrical current. If the illuminated pattern is designed to be an antenna pattern, then an antenna is created under illumination. Changing the illuminated pattern reconfigures the antenna. The goal of this contract was to demonstrate a simple reconfigurable antenna using an inexpensive, incoherent light source. The demonstration was successful: with a camera flash used in amateur photography and a 4"-diameter standard silicon wafer, a reconfigurable triangular ("bow-tie") antenna in the 1-3 GHz band was designed and constructed which radiated with an efficiency only 5 db less than a metallic antenna of the same structure. By reciprocity, the reconfigurable antenna will have the same efficiency when used as a receiving antenna. Furthermore, the camera flash had 10 times more energy than required, i.e., attenuating the flash output light 10 times did not change the antenna efficiency. This surplus of output light can be used in a liquid-crystal-display antenna mask controlled by a computer. A smaller reconfigurable antenna was constructed for and tested at 2-4 GHz to demonstrate a scaling law. This report presents the work done under the contract.

Experimental Set-up

The experimental set-up is illustrated in Figure 1. A camera flash illuminates a 4"-diameter silicon wafer through a mask whose opening forms the triangular antenna pattern. The illuminated pattern becomes the reconfigurable antenna which is connected to a microwave signal source via a strip line on the wafer. The receiving antenna is a metallic triangular on another 4"-diameter silicon wafer, of the same pattern as the reconfigurable antenna. The signal from the receiving antenna is connected to a spectrum analyzer. Most of the measurements were made with the camera flash 10 cm and the receiving antenna 8" from the reconfigurable antenna. The whole set-up was enclosed in a chamber lined with microwave absorbing materials. The set-up is shown in 2 perspectives in the attached photographs. Details of the components in the experiment are given below.

<u>The Antennas</u>

The triangular antennas were designed for a center frequency of 2 GHz or a wavelength of 15 cm. Following published data [J.D. Kraus, *Antennas*, 2nd Ed., McGraw-Hill 1988], the height of the triangle was made quarter wavelength and the full apex angle 60°, with the full antenna just fit within the 4" wafer diameter. Since the antennas were to be used free-standing with no ground plane on the back of the 0.25 mm-thick wafer, the vacuum wavelength had been used. On both the reconfigurable and the metallic antennas, a parallel strip metal transmission line was deposited to connect the center of the antenna in the middle of the silicon wafer to the OSM connector attached to the edge of the wafer. The antennas are illustrated in Figure 2. For experimental convenience, instead of straight triangular bases, circular arcs coincident with the wafer edge were used; no significant differences were expected. The impedance of a triangular

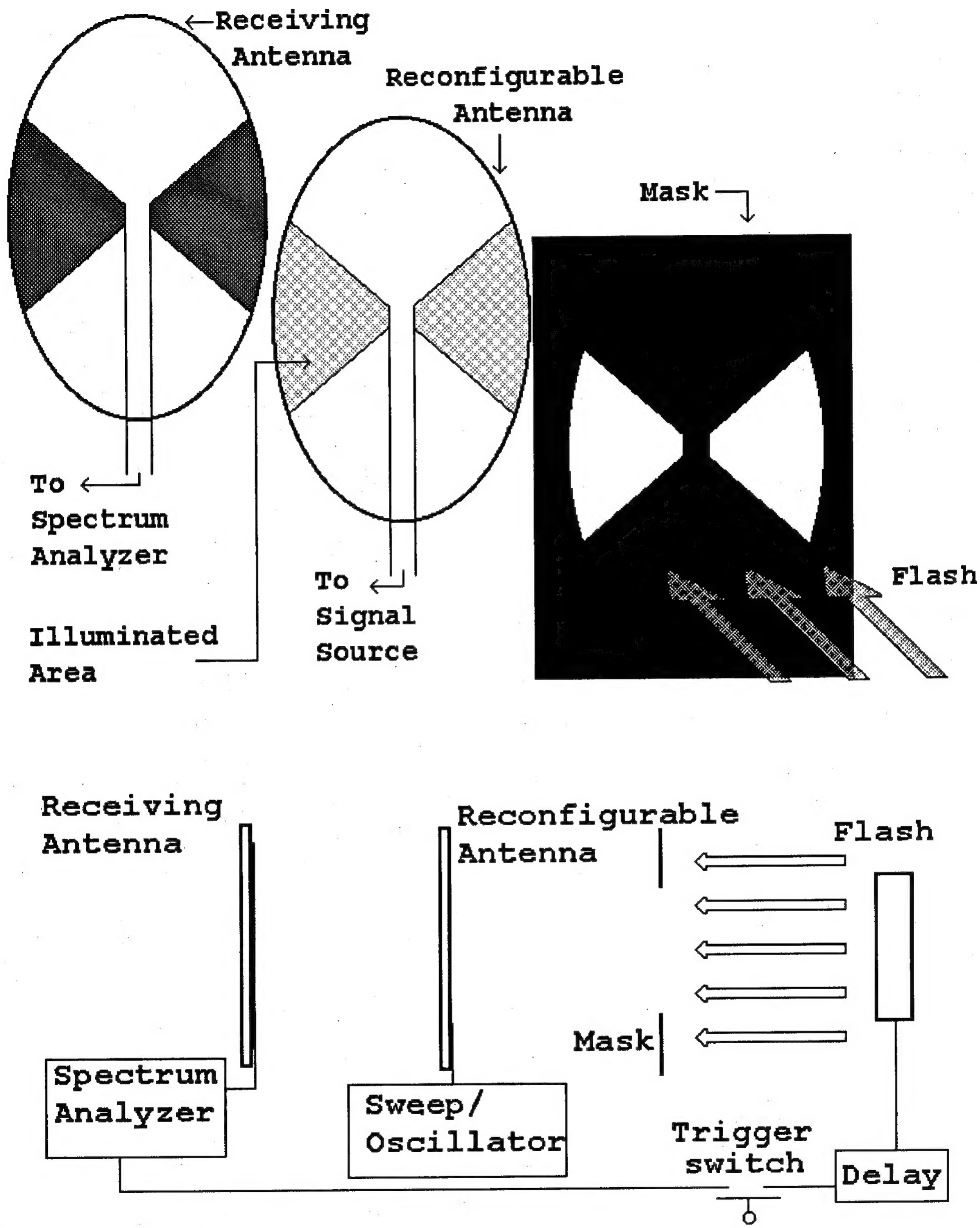
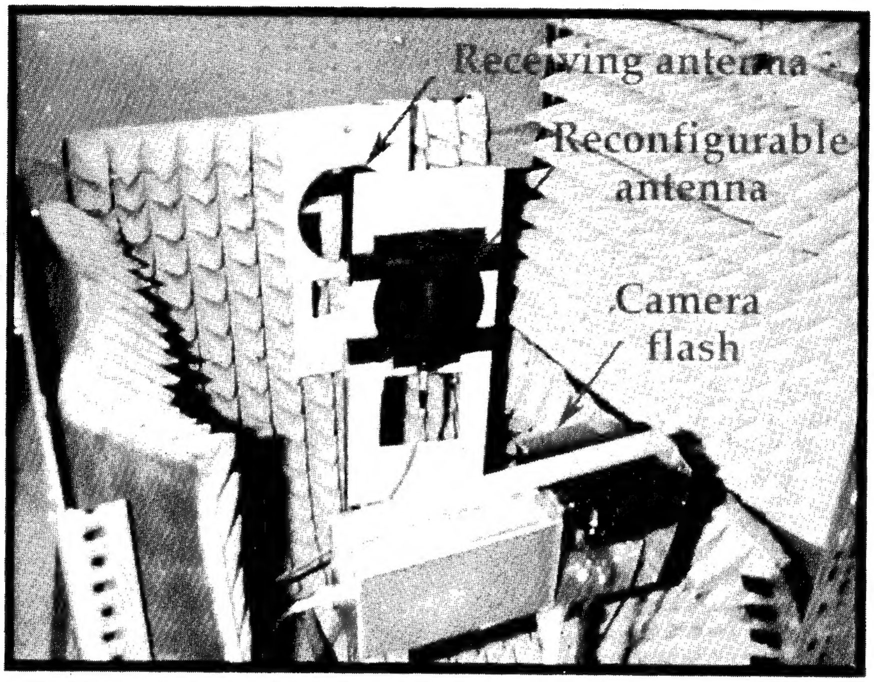


Figure 1 Experimental Set-up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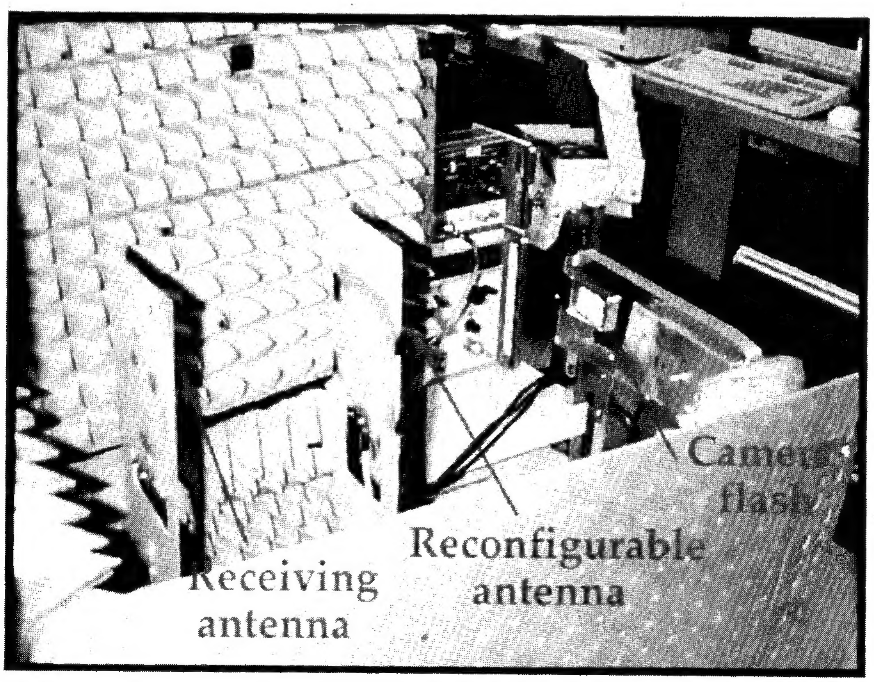
Reconfigurable
antenna
Camera
flash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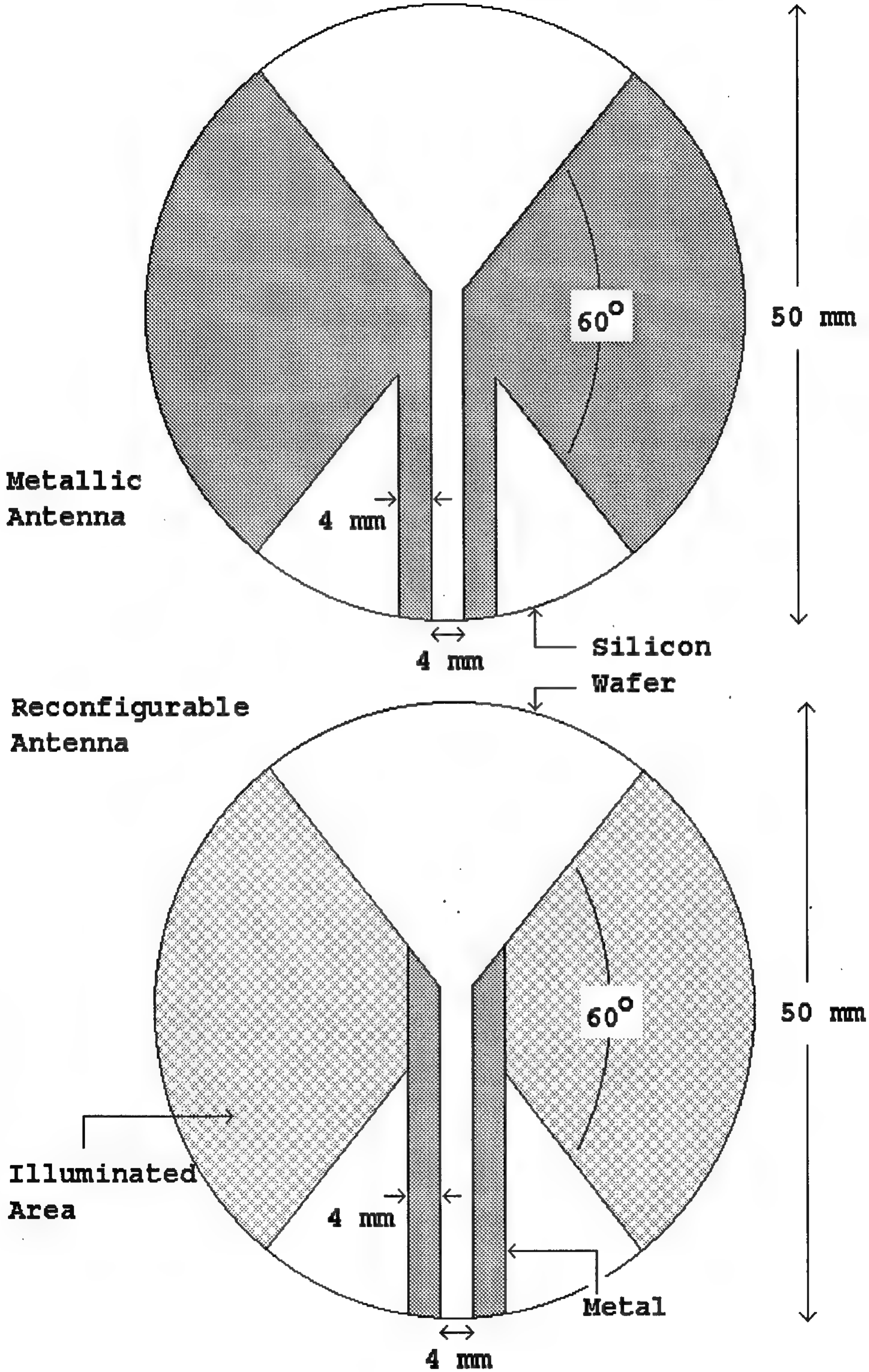


Figure 2 Triangular Antennas

antenna is on the order of 100 Ω [Kraus, *op. cit.*], and it is balanced. The characteristic impedance of the rest of the system (source and detection) was 50 Ω and signals were transmitted with coaxial cables (unbalanced). For this contract whose duration was short and the measurements were mainly of a comparative rather than absolute nature (reconfigurable vs metallic), it was decided not to address these mismatches. To measure the effect of mismatches, the reflection from both the metallic and reconfigurable antennas when driven with a signal source was measured using a directional coupler. The results, shown in Figure 3, indicate that no more than half of the power was reflected despite the mismatches, and the antenna systems were usable for comparing the reconfigurable antenna to the metallic.

Metal deposition on silicon was by thermal evaporation of chromium (200 Å) followed by gold (2,000 A). The surface resistivity was on the order of 1 Ω square.

The silicon wafers used were 4" in diameter, 0.25 mm thick, undoped with a resistivity specified to be greater than 1 kΩ-cm. Characterization of the materials is reported below.

<u>The Camera Flash</u>

The camera flash, National PE-243, was typical of consumer flashes used in amateur photography. Its optical output energy was measured by an energy meter to be a few Joules. A fast detector displayed its waveform in time (Figure 4a) with a duration of about 250 μs. The output spread over approximately 90°. No analysis was made of its sprectral content; however, its spectrum would most likely be similar to the typical xenon flash spectrum shown in Figure 4b, with the characteristic blue tint. Spectral components with photon energies less than the silicon bandgap (1.1 eV) are not absorbed, while those in the UV are absorbed on the surface where charge carriers recombine much faster than in bulk. Thus only the spectral range from the

Figure 3   Reflection from Antennas

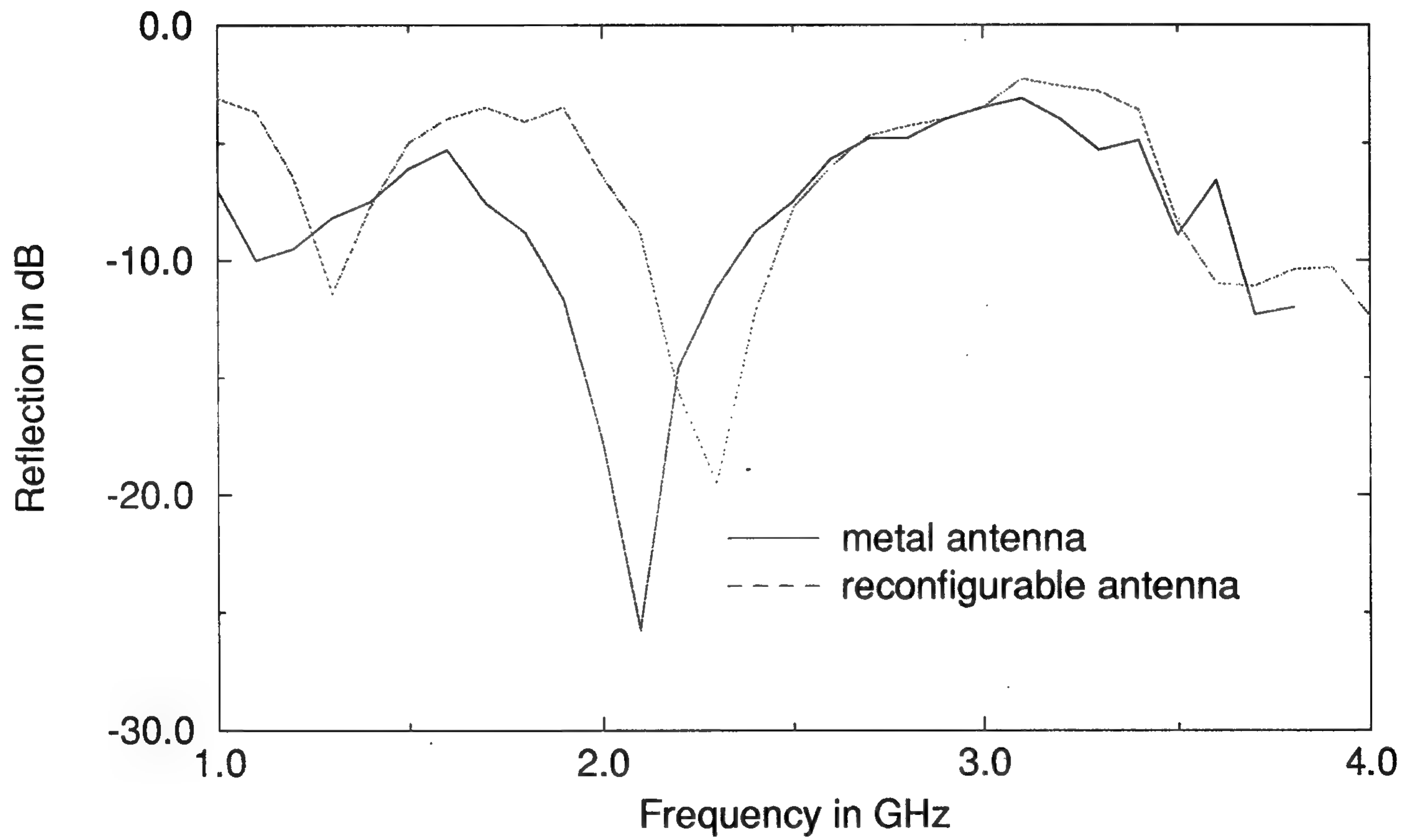
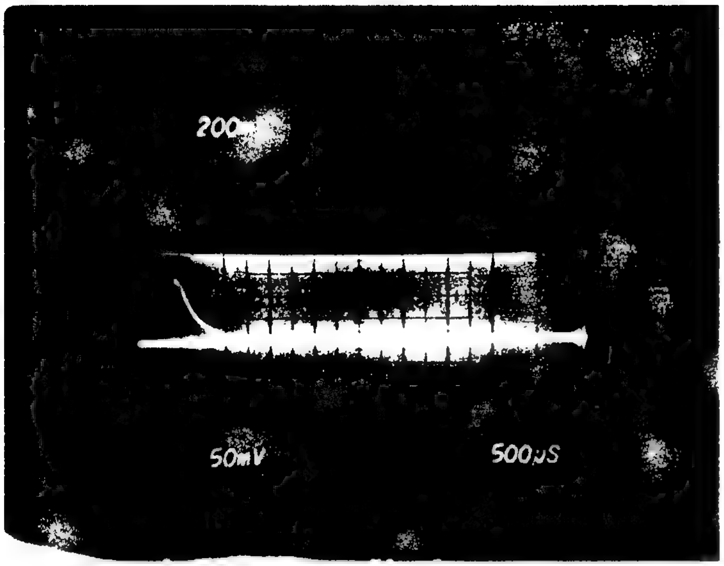


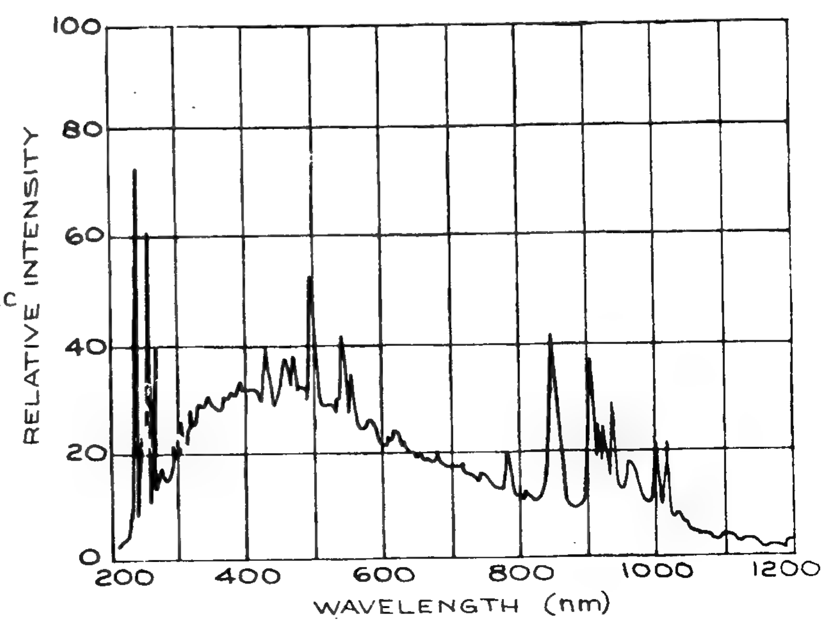
Figure 4 Flashlamp Characteristics

(a) Output Waveform
Horizontal: 500 µs/div



(b) Typical spectrum

Figure 4.85 Spectral distribution of intensity from an ILC 4L2 xenon flashlamp (51 mm long by 4 mm bore) operated in a critically damped mode with 10 J discharged in 115 µs. (Courtesy of ILC.)



From "Building Scientific Apparatus" by Moore, Davis, and Coplan, 2/ed Addison Wesley 1989

near infrared above the bandgap to the blue is effective in photoconduction.

Microwave Instrumentation

Two sweep/oscillators were used to cover the range 1 GHz - 4 GHz: HP 8620C with Plug-in 86222B (below 2.4 GHz), HP 8690B (2-4 GHz). Only one sweep/oscillator was used at one time, depending on the frequency at which measurements were made. The spectrum analyzer used was HP 8562A. For measurements of pulsed signals generated from the reconfigurable antenna, the spectrum analyzer was used in the single-frequency mode with a center frequency manually adjusted to the signal frequency. A microwave amplifier MiniCircuits ZHL4240 was used when needed.

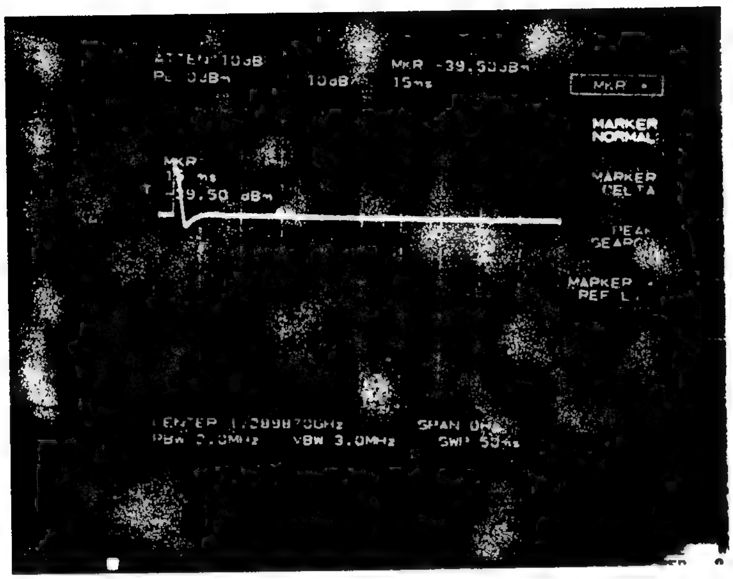
Measurements and Results

The main measurement was on the efficiency of the reconfigurable antenna in the 1-3 GHz range relative to the metallic antenna. Suppporting measurements were also made: antenna pattern, polarization, efficiency under different levels of illumination, and characteristics of the semiconductors used. A separate set of measurements were made on a reconfigurable antenna in the 2-4 GHz range to test a scaling law which states that the required optical illuminating power is proportional to the square of the radiating wavelength. These measurements and data are presented below.

<u>Efficiency of the Reconfigurable Antenna</u>

The efficiency of the reconfigurable antenna was measured using the set-up shown in Figure 1 in the following manner. The spectrum analyzer was set to single-frequency mode - it became in effect an oscilloscope with an narrow-band filter at the input whose center frequency was manually tuned to track the radiation frequency. A switch was used to trigger both the spectrum analyzer sweep (whose horizontal axis now represented time, not frequency) and, after a delay circuit, the camera flash. The signal source was fed to the reconfigurable antenna continuously; but the antenna radiated, and the spectrum analyzer detected a signal, only when the reconfigurable antenna was illuminated by the flash. A typical signal trace is shown in Figure 5 (the undershoot in the trace was pick-up). The signal level detected from the reconfigurable antenna was noted. The same measurement was repeated for different frequencies across the 1 - 3 GHz band. Next, the reconfigurable antenna was replaced by a metallic antenna of the same structure and the same measurements were made. The efficiency of the reconfigurable antenna relative to the metallic antenna is the ratio of the two sets of measurements, i.e.,

Figure 5
Typical Signal Detected on
Spectrum Analyzer in Single-
Frequency Mode
Total Horizontal Sweep: 50 ms



Relative efficiency of reconfigurable antenna

$$\frac{\text{power received by reconfigurable antenna}}{\text{power received by metallic antenna}}$$

The data are shown in Figure 6, from which the average efficiency of the reconfigurable antenna over the frequency range shown can be deduced to be about 5 dB less than the metallic antenna. At the distance between the flash and the reconfigurable antenna, the illumination was about 100 watts/cm^2. The 5 dB lower efficiency of the reconfigurable antenna was not due to insufficient optical power, as verified by the measurements presented next. The exact cause is not known, but it can be speculated to have come from the interconnection between the illuminated part and the metallic transmission line.

Efficiency vs. Illumination Intensity

To find the minimum optical intensity needed for the reconfigurable antenna, the flash output was attenuated at different levels and the efficiency measured. The set-up in Figure 1 was used, with the addition of neutral density filters in front of the flash lamp. The data, taken at 1.4 GHz, are shown in Figure 7. Almost no difference in efficiency was observed until the flash light was attenuated by ten-fold, implying that only about 10 W/cm^2 is needed.

Supporting Measurements on the Reconfigurable Antenna

Other measurements on the antenna were made to ensure that the reconfigurable antenna performed as expected.

(i) Pattern: The radiation from a triangular antenna is maximum in the direction perpendicular to the plane of the triangles, decreasing to zero on the plane. The receiving antenna was rotated around the axis through the apexes and parallel to the bases of the triangles (Figure 8). The

Figure 6   Efficiency of Reconfigurable Antenna

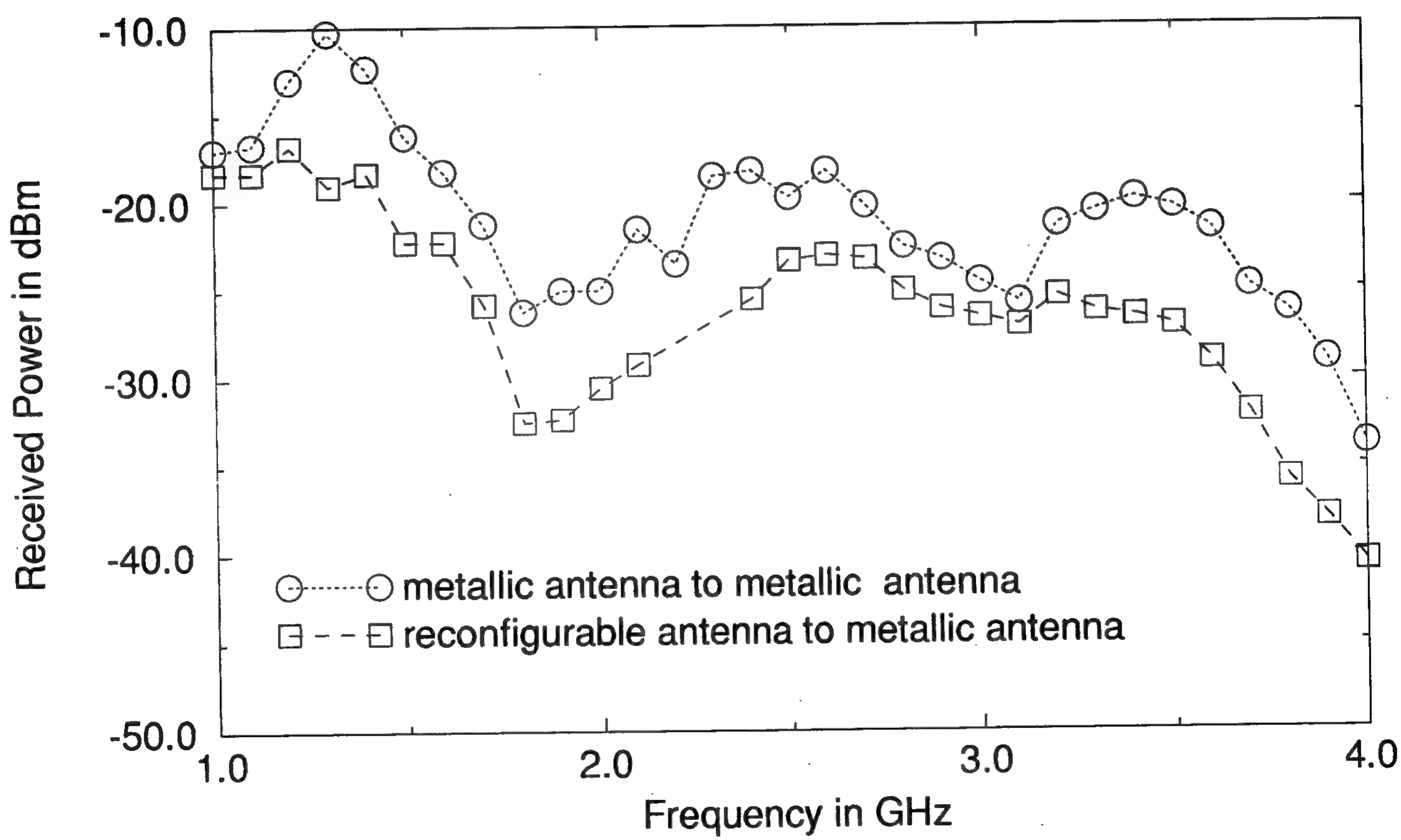
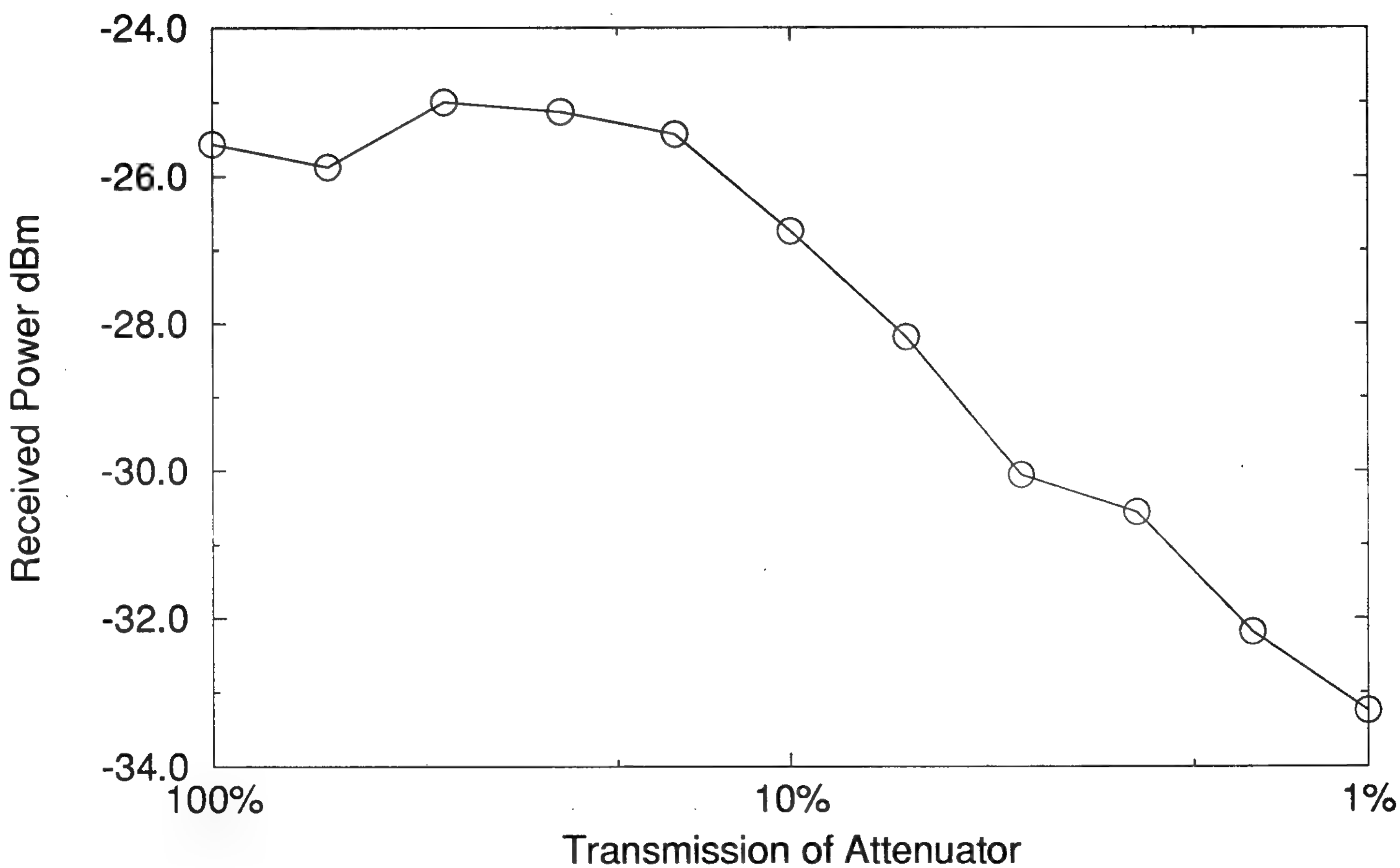


Figure 7 Efficiency vs Illumination



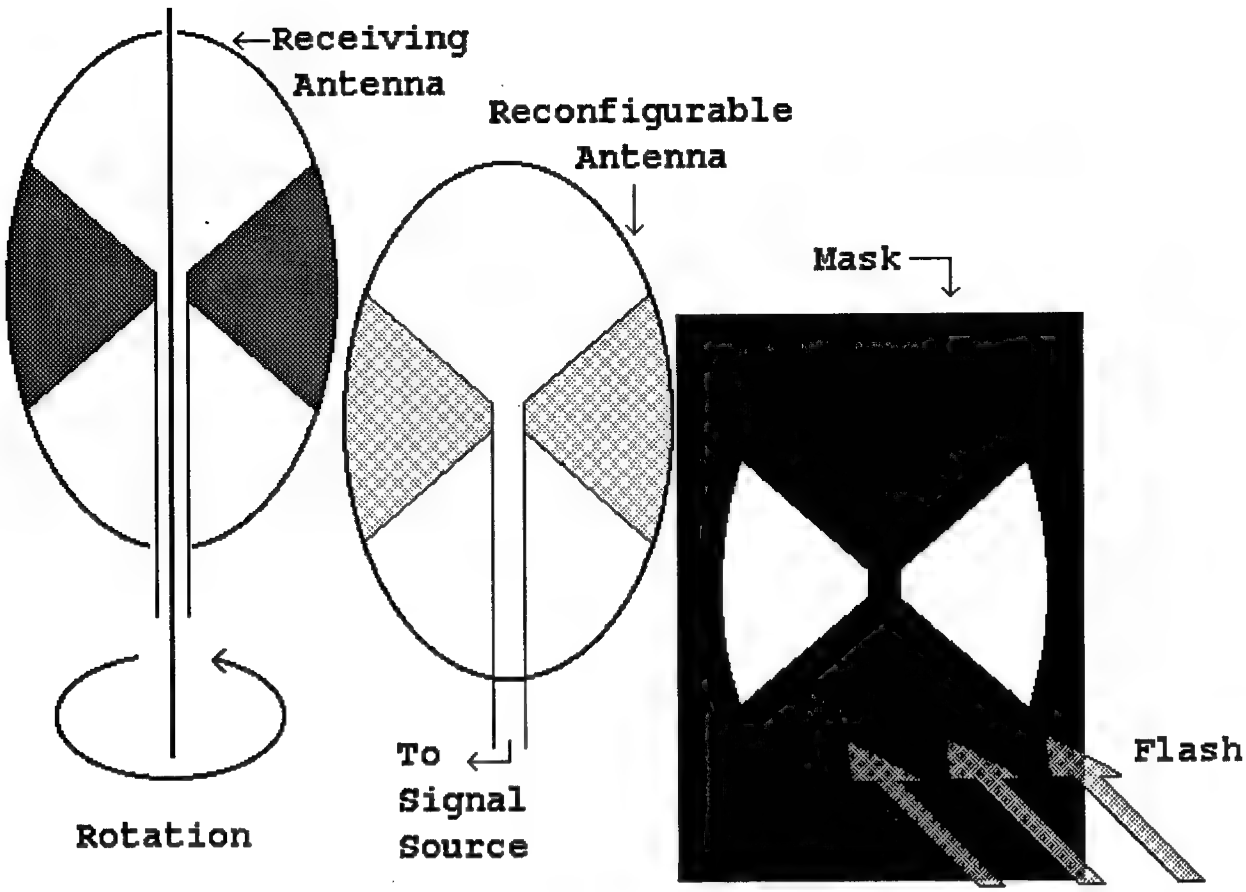
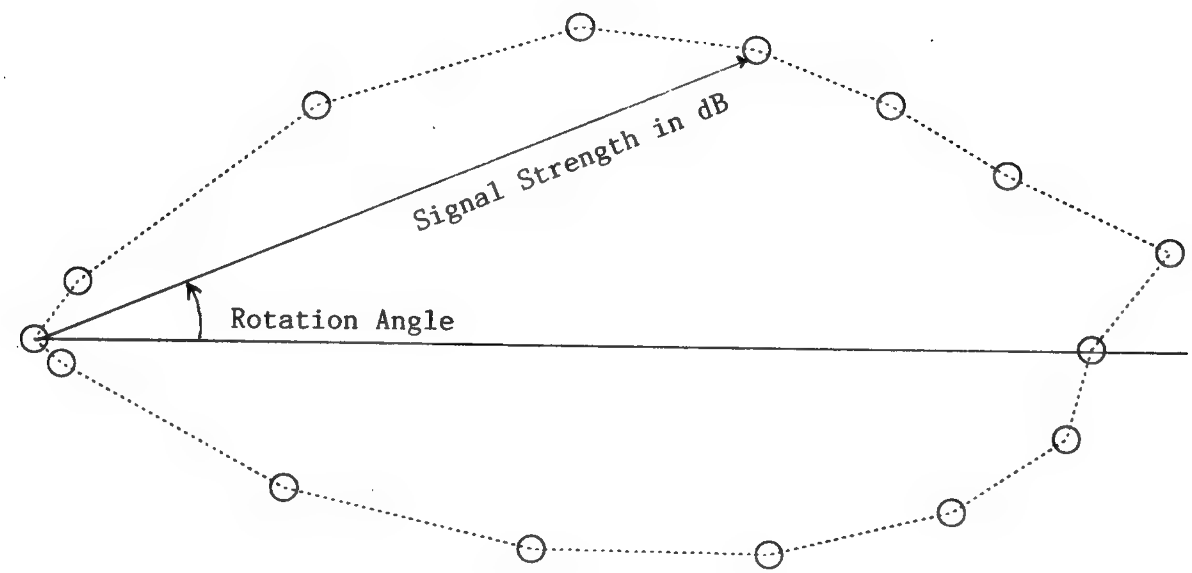


Figure 8
Pattern Measurement Set-up

Figure 9 Antenna Pattern



pattern measured agrees with theory and is shown in Figure 9.

(ii) Polarization: The triangular antenna radiates and receives waves polarized along the antenna plane and perpendicular to the triangle bases. Rotating the receiving antenna 90° around the axis perpendicular to the plane through the apexes (Figure 10) should eliminate all signals. The experiment was carried out and this was indeed the case.

(iii) Far/Near Field: The two antennas in the experiment were placed 8" apart to maximize signals and minimize spurious reflections from surroundings. Proper antenna measurements should be made in the far field. In the near field, the radiation intensity is approximately independent of distance from the source. In the far field, the intensity decreases quadratically with distance. The transition from near to far field occurs at a distance $\sim D^2/\lambda$, where D is the dimension of the antenna, and λ the wavelength. Since the separation of the antennas was close to the approximate transition distance, signal-vs-distance measurements were made using two identical metallic triangular antennas, one as source and the other reception, along the corridor at night. The results, taken at 2 GHz, are shown in Fig. 11, where the separation of antennas in other measurements is marked. It can be seen that measurements had been made just in the far field.

Scaling Law

In a previous contract with the Air Force (No. F3060293C0184) a scaling law was proposed which states that the illuminating power needed for reconfigurable antenna designed for a certain wavelength increases with the square of the wavelength. For the triangular antenna, the width of the antenna is about 1/4 wavelength, therefore the area to be illuminated is proportional to the square of the wavelength and the total optical power illuminating the pattern also is proportional to the square of the

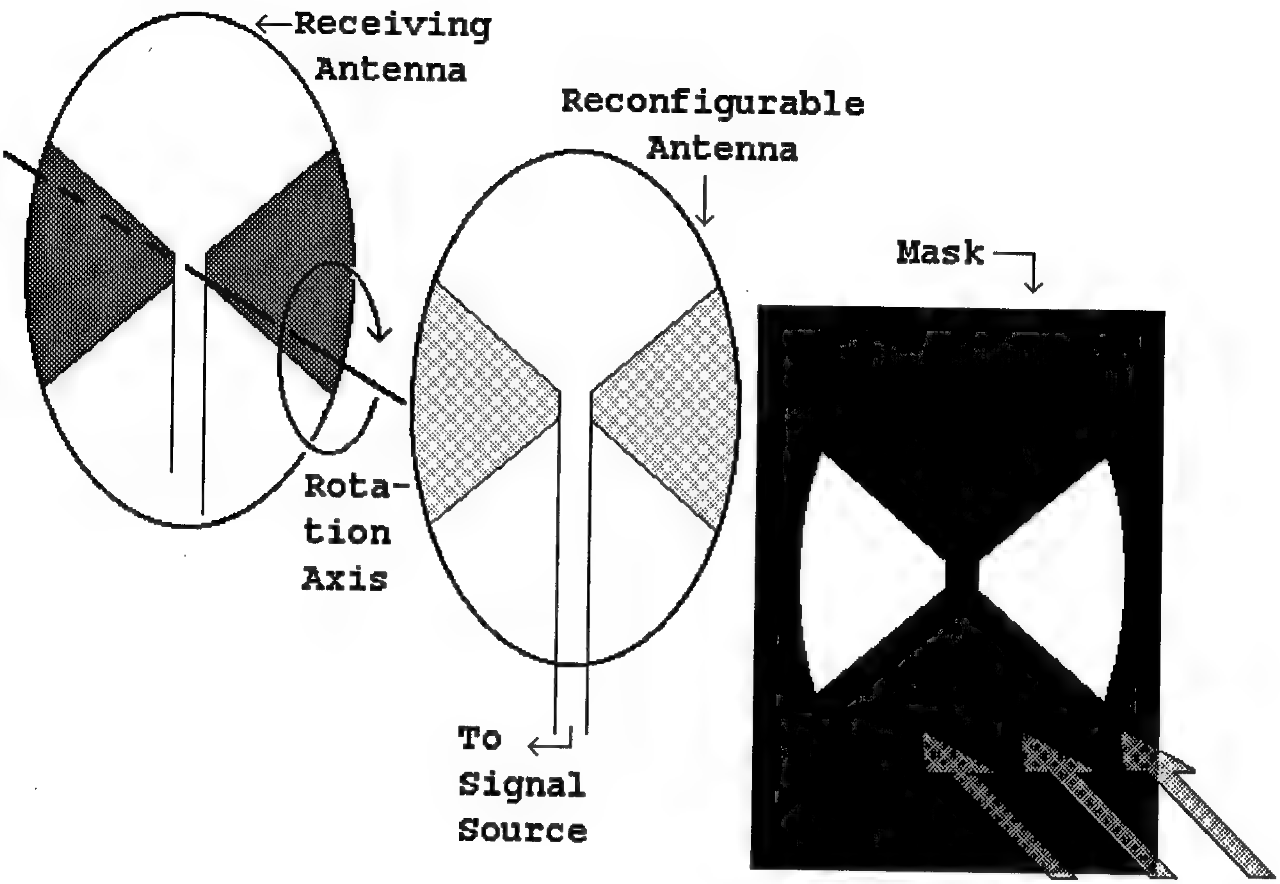


Figure 10
Polarization Check

Figure 11   Power vs Distance

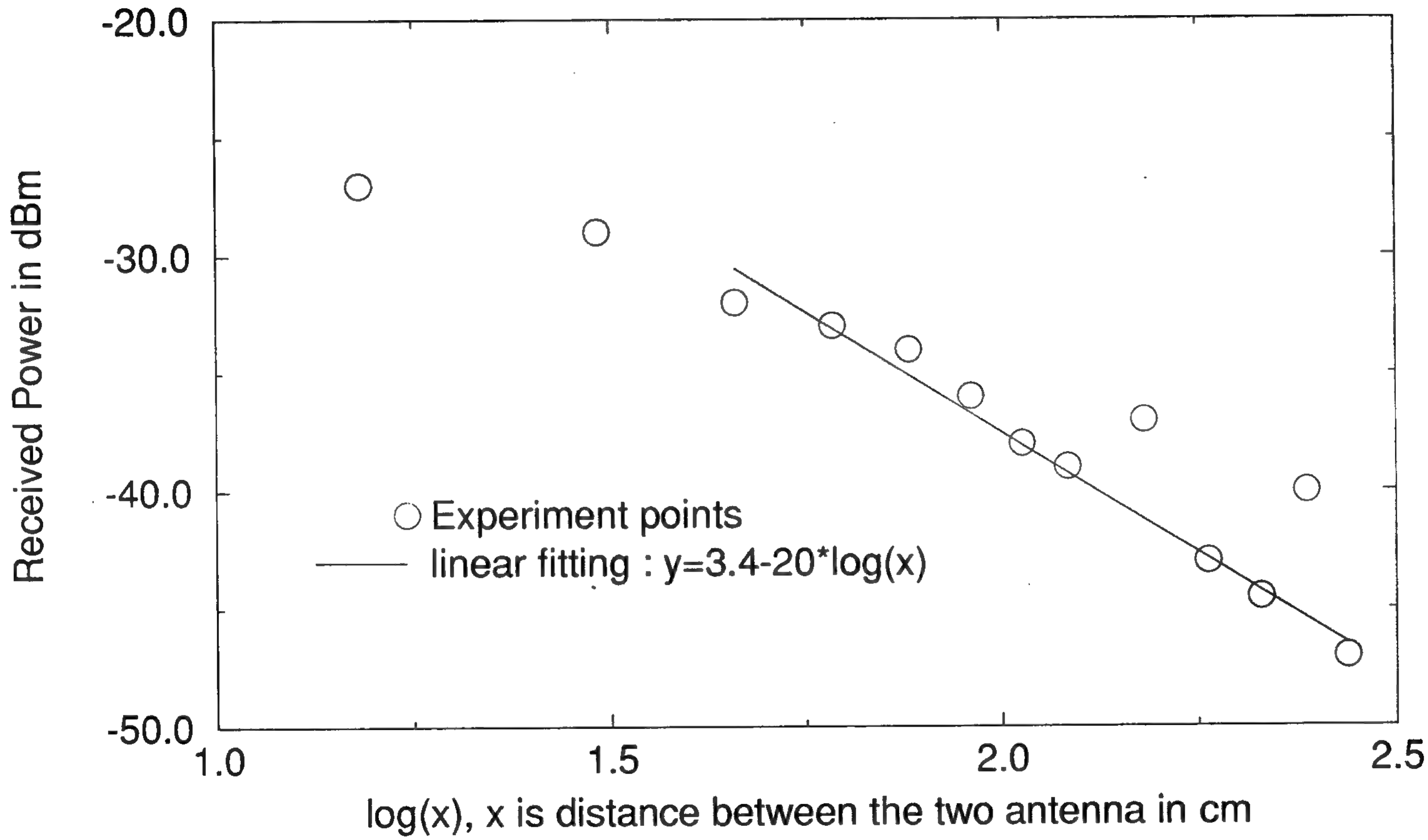
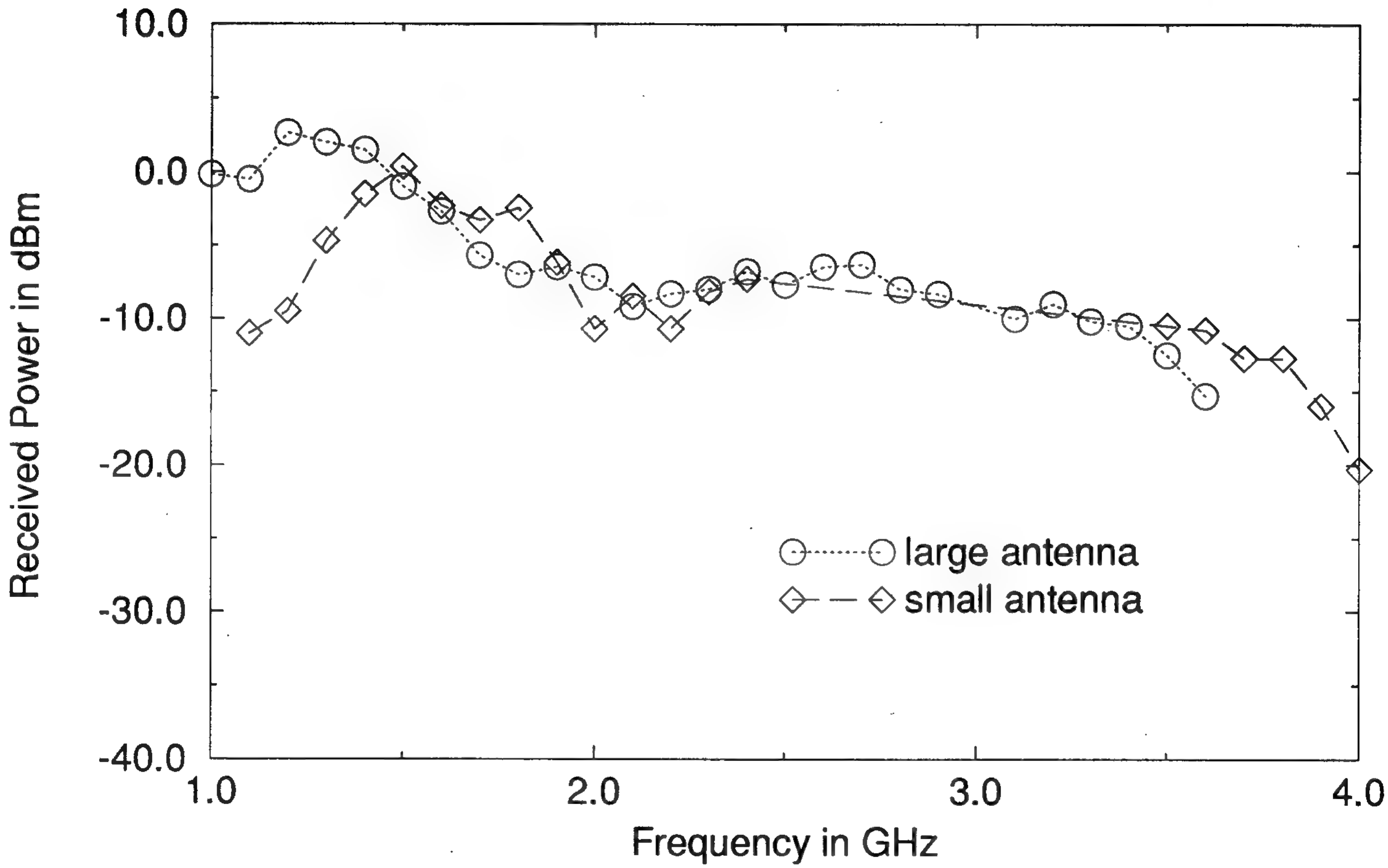


Figure 12 Comparison of two antennas



wavelength. To demonstrate this, a second reconfigurable antenna was constructed for a center frequency of 3 GHz by using a second mask with a width 2/3 that of the mask for the antenna at 2 GHz. The radiation from the smaller antenna was measured as before, and the results are shown in Figure 12 together with the data from the larger antenna. Since the optical *intensity* was the same in both cases, the *total optical power* intercepted by each antenna was proportional to the area of the antenna, or wavelength squared. At frequencies where both antennas operated, it is seen that both had similar performance, but with the smaller antenna requiring less optical power. Thus the scaling law was demonstrated.

Semiconductor Characterization

The important parameters of the silicon wafer for the reconfigurable antenna are mobility, carrier lifetime, and dark resistivity. The first two parameters determine the optical power needed, and the third should be high enough to make the wafer effectively insulating if not illuminated. The measure these parameters, the following experiments were carried out. The parallel strip lines on the reconfigurable antenna were used as electrodes, and the rest of the wafer was blocked from any light with a mask (Figure 13a). An area between the electrodes was used as a photoconductor, and biased with a DC voltage through a resistor in series (Figure 13b). The flash lamp illuminated the photoconductor, and the photo-resistance R was calculated from the measured voltage across the series resistance. If the carrier life-time τ is much shorter than the flash duration (verified later), then the mobility μ can be calculated from:

$$\mu = E_{photon} \, (w/L)/(\tau IR)$$

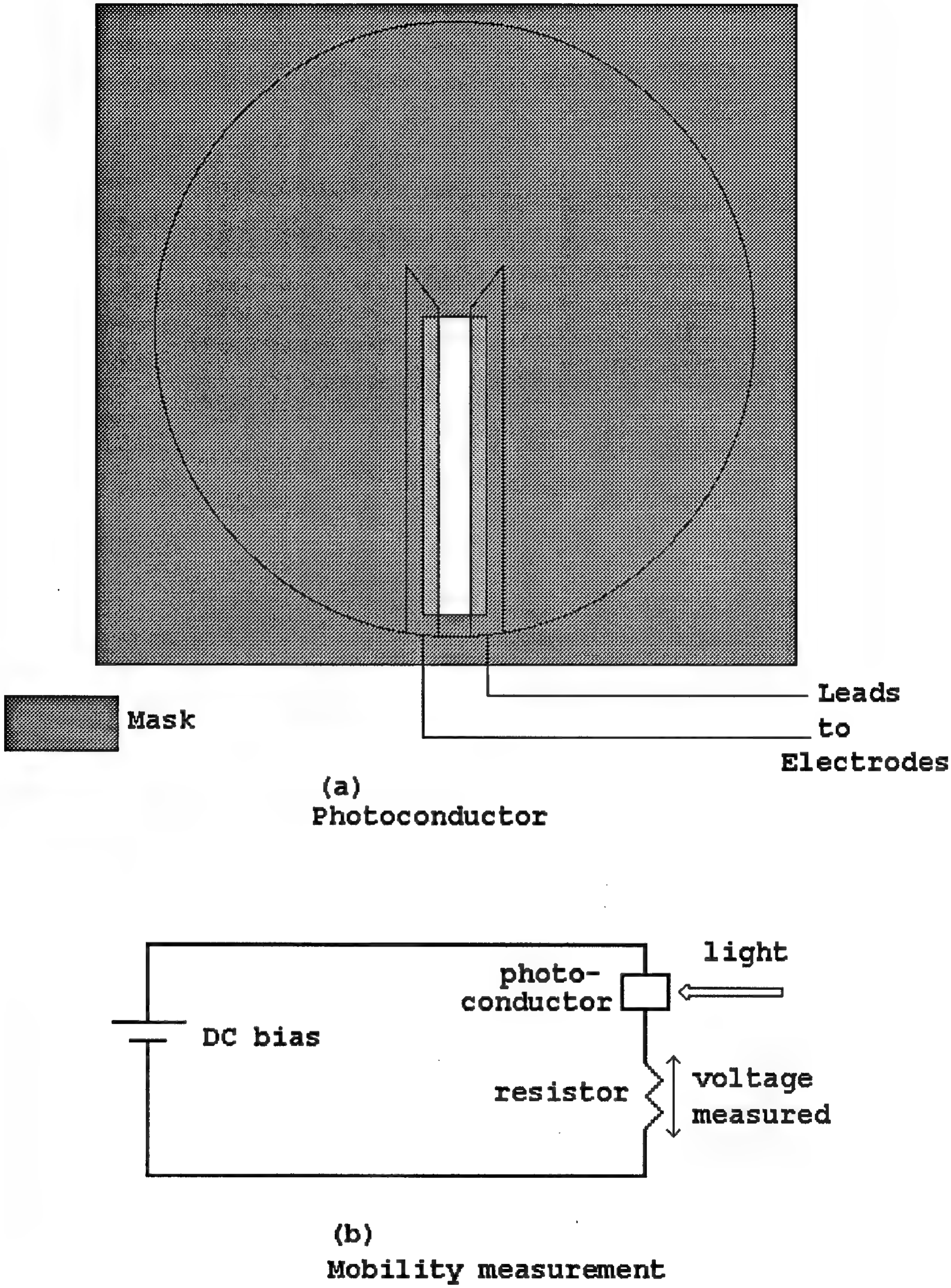
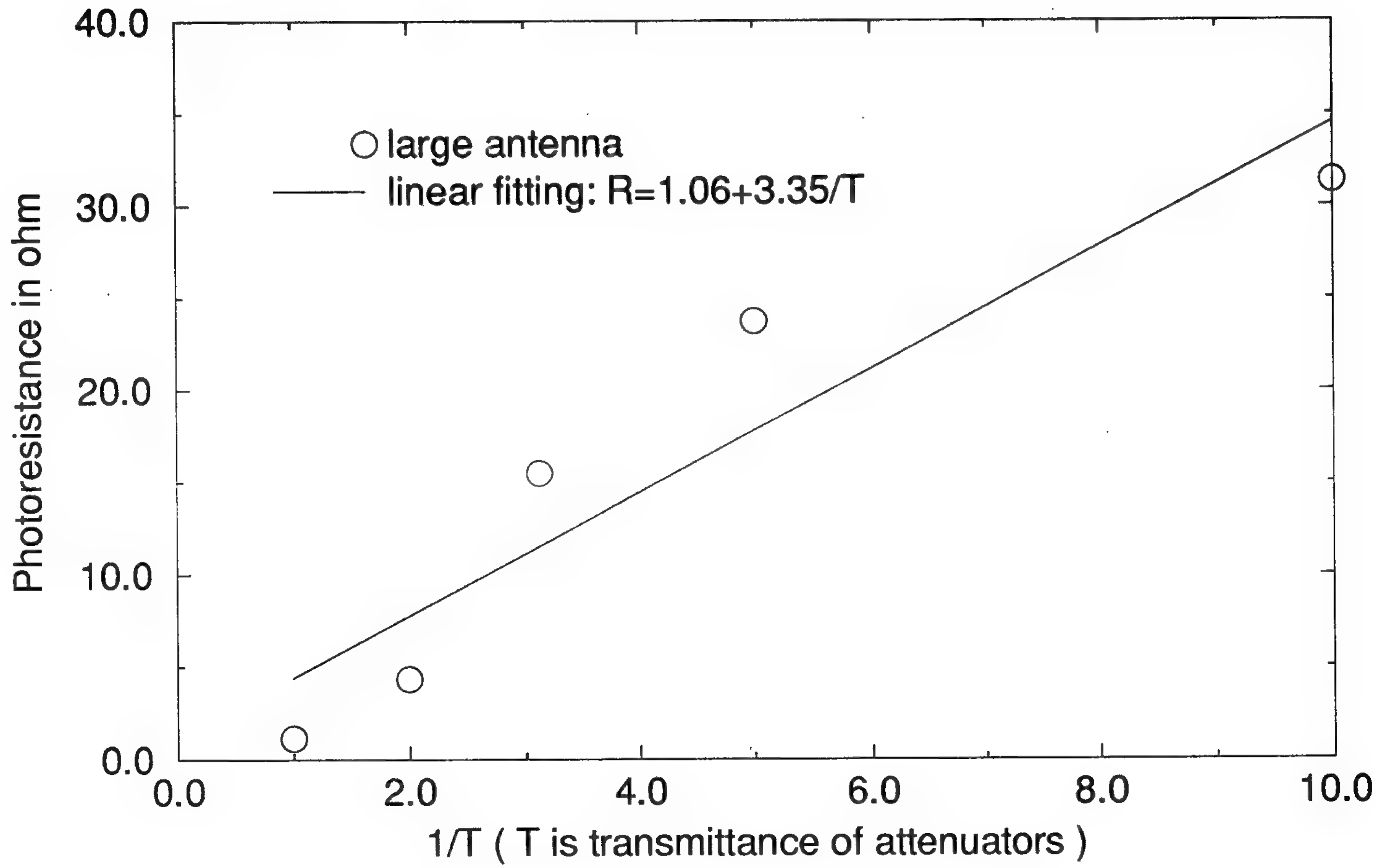


Figure 13
Semiconductor Characterization

Figure 14 Photoresistance vs light intensity



where E_{photon} is the photon energy, I the light intensity, w and L the gap width and length of the photoconductor respectively. With the flash lamp unattenuated, the photoresistance fell too low to be accurate, so measurement were made with different attenuators and the results are plotted in Figure 14. From these data, the mobility was estimated to be about $5 \times 10^{-3} / \tau(s)$ cm^2/V-s, with the carrier lifetime τ to be determined below. Extrapolating the photoresistance to infinite light intensity yields the contact resistance between the electrodes and the semiconductor, about 1 Ω. To determine the carrier lifetime, the flashlamp was replaced by a YAG laser which put out 15 ps at 1.06 μm, and the photo-conductance was observed with a fast oscilloscope to have lifetime of about 5 μs, which is interpreted as the carrier lifetime τ. With this additional information, the mobility was then estimated to be about 10^3 cm^2/V-s. The values of both the mobility and the carrier lifetime are very typical.

The dark resistivity was simply estimated from the dark resistance measured between the two electrodes to be about 10 kΩ-cm, well within the specification of the material and adequate for the experiments.

Discussion of Results and Recommendations for Further Work

The experiments performed demonstrated the practicality of the reconfigurable antenna illuminated with an inexpensive, incoherent optical source. The fact that even a common camera flash has ten times more energy than required points to further development of a computer-controlled reconfigurable antenna. The mask can be replaced by an inexpensive liquid-crystal-display panel, such as those used in portable television sets, whose transmission is controlled by a computer.

In a previous contract with the Air Force (No. F3060293C0184), an estimate was made of the required optical power to illuminate an antenna on silicon: 300 W at 1 GHz, with wavelength measured in silicon with mobility and carrier lifetime of 10^3 cm^2/V-s and 20 μs respectively. Scaling the power by the parameters to those in the experiments verifies the estimate.

As already noted, the 5 dB difference in efficiency between the reconfigurable antenna and the metallic antenna was not due to insufficient illumination. Its cause may well come from the electrical contact between the illuminated part and the metallic part of the antenna. This should be looked into further.

It should be noted that all the components of an optically illuminated reconfigurable antenna are present in a small photo-copying machine: photoconductor (the drum is coated with selenium, for example), the lamp, the imaging system. With commercially available components, it should be able to design very inexpensive reconfigurable antenna systems.

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d. Promotes transfer of technology to the private sector;

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